Phreatic Eruption Clouds: the Activity of La Soufrière de Guadeloupe, F.W.I., August - October, 1976

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ABSTRACT

From August to October, 1976, La Soufrière de Guadeloupe was observed, and recorded with an automated sequence camera and numerous handheld cameras. During the period of observation, the nature of volcanic activity ranged from mild steam emission to moderately energetic phreatic eruptions.

Background fumarolic activity (steam emission) was characterized by the emission of generally tephra-free steam clouds 50 to 150 m above the summit. The clouds rose buoyantly above the vent and were blown downwind at prevailing wind velocities. Phreatic eruptions were well-documented on September 22, October 2, and October 4. In the latter two eruptions, small bursts of tephra-laden steam erupted at intervals of 30 to 45 min. and rose from 350 to 500 m above the summit. In the largest observed eruption, that of October 2, the steam and tephra cloud rose to a maximum height of 600 to 650 m in 20 min. A white vapor cloud and a medium gray, tephra-laden cloud were erupted simultaneously from the summit vent and both were surrounded by a vapor collar; the clouds were thoroughly mixed within 1 km downwind of the summit. The concurrent growth of clouds from separate vents (summit and flank) implies a common source. Simultaneous eruption of tephra-free and tephra-laden clouds from the same vent is puzzling and implies: (i) lateral changes in the degree of alteration of dome rocks along the elongate vent, hence erodability of the dome lavas, or (ii) differences in the gas velocities. These «mixed» clouds moved westward, downwind and downslope as a density current, along the watersheds of the R. Noire and R. des Pères with an approximate velocity of 10 to 25 m/sec. Upon reaching the sea the clouds continued to move forward, but at a decreased velocity, and spread laterally, having left behind the restrictions of valley walls. A thin gray veneer of moist tephra, ranging from several cm thick near the dome to less than 1 mm thick several km downwind, was deposited along a narrow corridor southwest of the summit. Tephra from the phreatic eruptions consisted mostly of hydrothermally altered lithic, mineral, and glass fragments derived from dome lavas; no fresh (juvenile) pyroclasts were present in the tephra.

Absence of juvenile tephra at La Soufrière supports the view that activity was due to groundwater circulating in a vapor-dominated geothermal system, probably driven by a shallow heat source. At La Soufrière, most vapor-dominated systems are located in elevated areas of groundwater recharge where groundwater movement is downward and outward. The sporadic phreatic eruptions may be related to the rate of recharge of meteoric waters within the dome, the decrease in pore pressure during fortnightly tidal minimums or both. Whatever the triggering mechanism, vapor-dominated fluids eroded vent walls during phreatic eruptions and carried out fine-grained, hydrothermally altered, pre-existing dome material as tephra.

INTRODUCTION

La Soufrière de Guadeloupe is an active volcano located near the southern tip of the Island of Guadeloupe, French West In-

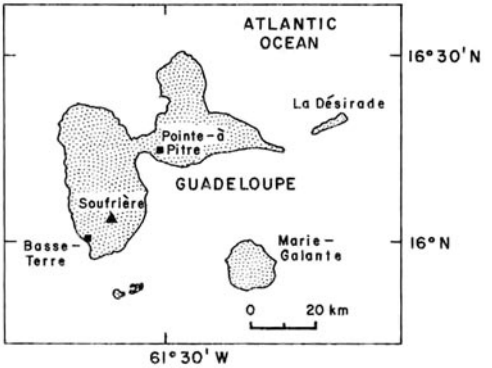


FIG. 1 - Location map, Island of Guadeloupe.

dies (Fig. 1). It is composed of an older volcanic massif capped by a steep-sided dome that is 700 m in diameter and rises approximately 470 m above the massif surface (ROBSON and TOBLIN, 1966; LASERRE, 1961). La Soufrière, the highest point on the island (1,467 m), towers above the populated regions, the largest being the towns of St. Claude, Basse-Terre and Capesterre. During summer and autumn, 1976, increased seismic activity and phreatic explosions at La Soufrière provoked the evacuation of most of the inhabitants of the region and marked the beginning of multidisciplinary studies of the volcano by scientists from France, U.S.A. and Trinidad. The objectives of the small group from the Los Alamos Scientific Laboratory were: (1) Document and study eruption clouds, (2) Sample and characterize tephra, (3) Measure the tilt of the volcano, both as a predictive tool and to analyze ground deformation associated with the phreatic activity. This paper presents the results of the eruption cloud study; our results from the tephra and tilt studies will be presented elsewhere.

GEOLOGIC SETTING

The Island of Guadeloupe is one of a line of primarily volcanic islands that form the Caribbean Arc. The island is divided into two major parts (Fig. 1). The northeastern part is mainly an uplifted limestone platform, whereas the southwestern, or Basse-Terre, part is composed of NNE-trending chain of Post-Miocene volcanoes.

The «basalt complex» beneath the dome consists of altered and eroded volcanic rocks (LASERRE, 1961). Volcanic agglomerates, breccia, tuff units and lava flows buried beneath a carapace of lateritic clay are locally exposed within canyon walls.

RECENT ACTIVITY

Historic eruptions, as summarized in ROBSON and TOMBLIN (1966), have been of small magnitude consisting of phreatic explosions and fumarolic activity, and the generation of small lahars. The last Peléean activity occurred between 1277 and 1577 A.D. (C_{14} date of 550 ± 150 years - BRUET, 1953). Most of the activity has been concentrated along the NW-SE trending fracture system on the SE side of the dome. Some of the past activity has been observed near the summit at Gouffres Dupuis and Tarissan (ROBSON and TOMBLIN, 1966).

During October, 1956, steam and gray tephra were erupted from a new fissure on the southeast slope of the dome. Large blocks were erupted onto the surface near the vents and a thin layer of fine-grained tephra was deposited west of the fissure along a 12 km long, 2 km wide area (BARRABÉ and JOLIVET, 1958). About 10^5 m^3 of tephra were erupted between October 19 and October 24. The 1956 activity was, in most ways, similar to the activity described in this paper.

TECHNIQUES USED IN THE STUDY

The phreatic activity of La Soufrière was recorded with a stationary automated sequence camera and numerous hand-held cameras. (These are described in the Appendix). Although photographic studies were hampered by bad weather, a number of freatic eruptions as well periods of typical fumarolic activity were well documented. Formulae used in analyzing vent velocities are detailed in the Appendix. Tephra from each of these eruptions, and may more not photographed, were collected for petrologic analysis.

Table 1 – *Activity Observed during the Eruption Cloud Studies*

Aug. 30: 1040 AST. Phreatic explosion carried steam and tephra 2 km downwind from the summit. Blocks fell on dome and near-summit car park. No photographic data; eruption clouds mixed with atmospheric clouds. Explosions followed a period of increased seismicity. Small lahars generated.

Sept. 14: 1922 AST. Phreatic explosion and rock avalanche. Vegetation was flattened and/or defoliated over an 800 m long, wedge-shaped area. Wind directed air fall to sea near Vieux Habitants. Not photographed or observed.

Sept. 22: 0619-0627 AST. Phreatic explosion with ash cloud rising 3500 m above vent. Documented from 0620 to 0630. Tephra-fall to west; 3 mm of tephra at geophysical observatory (Parnasse). Explosive phase ceased by 0645.

Sept. 23: 1200. Mild fumarolic activity observed.

Sept. 26: 0602-0700. Mild fumarolic activity with very small phreatic explosion observed at 0635.

Sept. 28: ~ 1200. Mild activity, with small phreatic explosions. Tephra fall within 1 km, dispersed steam and tephra cloud moving down the Rivière Noire.

Sept, 29: 1730. Quiet fumarolic activity photographed.

Oct. 2: 1350-1750. Fumarolic activity. Major phreatic explosion starting at 1638. The tephra-laden cloud rose ~ 630 m above the summit. The clouds flowed down the valley of R. Noire and across the sea. Activity had subsided by 1750 when observation was terminated by darkness.

Oct. 3: 1100-1300. Fumarolic activity produced a very dilute cloud that flowed west, along canyons radial to the summit.

Oct. 4: 1100 AST. Marked increase in fumarolic activity. *1150 AST.* Phreatic eruption, with cloud rising to ~ 160 m above the summit, flowed west. Tephra fall over summit and along the valley of R. Noire. 1245 AST; Phreatic explosions. Lahars developed, flowing down dome flanks. *1618-1720:* Numerous small phreatic explosions, with clouds rising to 250 to 300 m above the summit.

Oct. 8: 1200. Mild fumarolic activity.

Oct. 9: 0800. Mild fumarolic activity observed.

Oct. 10: 1111 AST; 1 m, 2 sec.harmonic tremor, coinciding with increased tephra emission. Tephra emission from phreatic explosions for 20 to 30 min., depositing 4 mm thick layer at summit car park.

Oct. 11: All day; quiet fumarolic activity.

BACKGROUND FUMAROLIC ACTIVITY

Background fumarolic activity occurred nearly continuosly between phreatic explosions during the period of observation. Several days of this fumarolic activity were photographed with the Automax camera. A typical synthesis of these observations is presented here to characterize the activity.

Pale gray or white steam clouds rose buoyantly from vents located at the summit and along the southeastern fissure to a height to 20 to 100 m. The long axes of visible clouds extended downwind for distances of 250 m to several km (Fig. 2). Generally the clouds were wind-sheared, flowing to the west and down the valley of the Rivière Noire. The smell of sulfur compounds was detectable for 3 or 4 km downwind, although no clouds were visible at that distance. The clouds were either continuous or broken into sections 40 to 85 m long. Although very little tephra was entrained during the background activity, small visible tephra-falls were occasionally carried for 100 to 350 m downwind.

After *small* phreatic explosions, the cloud changed from white to a medium gray (presumably a reflection of the tephra content) and rose to 2 or 3 times the height to the steam clouds of the background fumarolic activity. In windless conditions, especially during the evenings just after sundown, the steam plumes rose as thin vertical columns from 500 to about 1000 m above the summit.

OBSERVED PHREATIC ERUPTIONS

The most completely documented eruptions were on October 2 and October 4. The eruption of October 2 was recorded by the Automax camera and by observers

FIG. 2 – Mild phreatic activity, September 28, from the location of the Automax camera on the Plateau du Palmistes, 4 km SE of La Soufrière, The main (summit) vent, that erupted steam and a small amount of tephra, is to the left. The pale gray streak left (southwest) of the summit consists of tephra-fall and laharic breccia. The plume to the right is rising from a fissure vent on the southeast flank of the dome.

located at Vieux Habitants and Marigot. On October 4 the activity was photographed by the Automax camera and observers located at Basse-Terre and near the summit.

Oct. 2, 1976:

Throughout most of the day, there was fumarolic activity, with several small phreatic explosions. The activity was at two vents; the summit (Gouffre Tarissan) and on the southeast flank along a new fracture system (near the Cratere du Sud of FEUILLARD *et al.*,) (SEE Fig. 2).

The maximum height of the eruption clouds above the vents (ΔH) is described in Fig. 3, along with the estimated escape velocities of gases at the summit vent (W_0).

During background fumarolic activity, cloud heights at both vents ranged from 60 to 100 m. During phreatic explosions, clouds at both vents increased in size concurrently (Fig. 3), reaching elevations of 200 to 500 m. The clouds were sheared off by winds passing over the summit, moving westward, downwind, for distances of 40 m to 1 km. Immediately after an explosion, the clouds were dark gray and heavily laden with tephra. Tephra falls were visible for several hundred meters downwind of the vent.

At 1638 hrs., a large phreatic explosion lasting 7 minutes took place. Clouds rose to 623 m above the summit vent and 452 m above the southeast fissure. Based on analyses of the Automax camera photography, this event was over by 1657 hrs., with fumarolic activity continuing until dark (1750 hrs.).

Observers at Vieux Habitants saw the beginning of the phreatic eruption at 1638 hrs. and followed the development of the eruption cloud during its westward movement to the sea. The eruption cloud from the summit vent, the only vent visible as the flank vent was concealed behind the dome, had two distinct parts; to the southeast it was medium gray and to the northwest it was white. Both were mixed and moved downwind.

When the cloud reached a height of about 600 m, the buoyant rise was over-

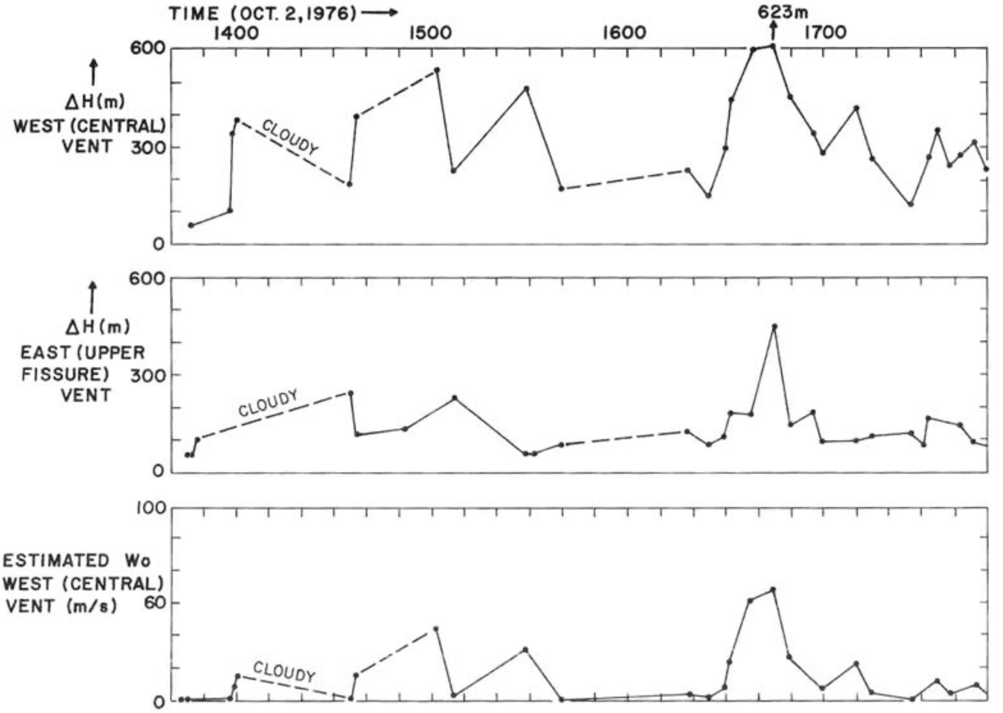
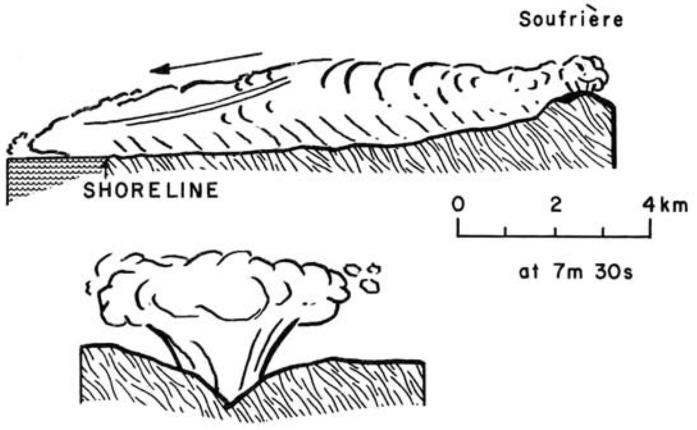


FIG. 3 – Graph of ΔH (plume rise above the vent) and W_0 (vertical exit velocity at the vent mouth) versus local time for the eruption of October 2.

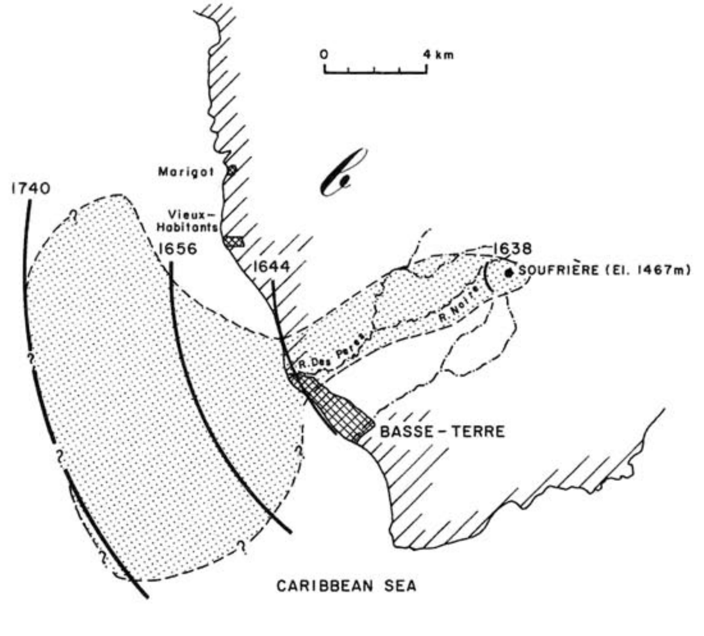
come by wind and the cloud moved toward the west. It approximately followed the valleys of Rivière Noire and Rivière des Pères, moving as a tephra-laden density current. As the cloud moved forward, confined by ridges parallel to the valley, there was some upward motion (Fig. 4). Viewed from the northwest side, the lowest km of the density current was curved upward and outward with a striated appearance. Above this level, for a height of 0.4 to 0.8 km, it flared out into a massive, turbulent form (Fig. 4). As the cloud moved down the valley, a thin, veil-like wreath of vapor was pushed ahead of it. The cloud moved along the valley to the sea with an average velocity of ~ 25 m/sec, considerably faster than the wind speed of about 10 m/sec. When the cloud reached the sea and was no longer confined as a density current by valley walls, it spread laterally as well as forward. By 1740 hrs, about an hour after the eruption began, the cloud had spread to the north across the sea by at least 7.5 km, cutting off the view of the sun from Marigot Village. As the cloud was moving over the sea, it was still preceeded by a thin vapor veil several hundred meters thick and by a low, thin, light gray cloud moving as a density current immediately above the water surface (Fig. 5). The full extent of the cloud to the west and south was not determined. The cloud left thin (mm-scale) layers of fine-grained (clay and silt-size) tephra along the river valleys down which it flowed.

Oct. 4:

Phreatic explosions were observed from several locations throughout the day. The earliest activity was observed at close range, from the summit car park at Savane a Mulets (1050 to 1150 hrs). The activity was solely at the summit vent. As was observed on Oct. 2, there were two


Soufrière
SHORELINE
0 2 4km
at 7m 30s

a


0 4 km
Marigot
Vieux-Habitants
1740
1656
1644
1638
SOUFRIÈRE (El. 1467m)
R. Noire
R. Des Peres
BASSE-TERRE
CARIBBEAN SEA

b

cloud types at the vent; a dark gray turbulent cloud in the center, flanked on the ends of the elongate fissure-like vent by pure white steam clouds. Surrounding both clouds was a thin veil of vapor (Fig. 6). The clouds rose only 60 to 70 m above the summit before being swept downwind to the west. All three clouds were mixed within 1 km into a single medium gray cloud that moved down-slope into the valley of the Rivière Noire. The top of this cloud dropped to a level 100 to 200 m below the summit 4 km downwind (to the WSW). At this distance it began to rise again, to an elevation of about 2.5 km (about 1 km above the summit), as a thin, light gray, vapor cloud (Fig.7). This may have been related to the pattern or «flowlines» of wind passing over the summit and not to flowage of a density current. These clouds contained much less tephra than the one described on Oct. 4.

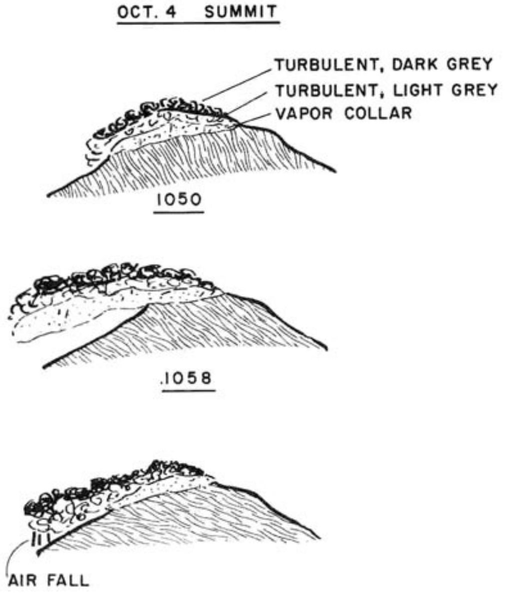


FIG. 6 – Sketch of the summit during the phreatic eruptions of October 4; based on photographs taken from Savanes à Mulet (summit parking lot). A turbulent dark gray, tephra-laden eruption cloud was flanked by a white to light gray steam cloud and a diffuse «collar» of vapor. These clouds rose only 60 to 70 m above the summit before they were swept downwind.

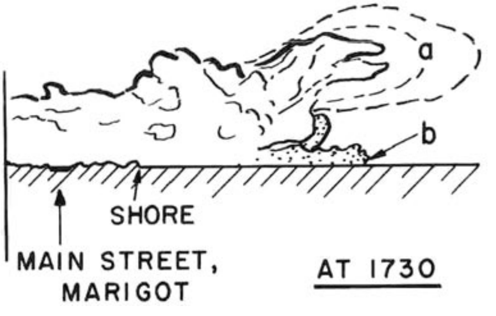


FIG. 5 – Sketch of the terminus of the steam and tephra cloud that flowed over the sea, as a density current at 1730 hrs. The main body of the medium-gray cloud was preceded by a low, more rapidly moving cloud (b) and a thin vapor veil (a).

Activity similar to that described above continued through the day, with ash-fall visible below much of the length of each cloud. Phreatic activity later in the day (1600 to 1750 hrs) is summarized in Fig. 8. The cloud heights (ΔH) varied from 20 to 250 m until the wind speed dropped and the air was calm. Mild activity produ-

← FIG. 4 – (a) Schematic drawing of the density current resulting from the phreatic eruption of October 2: (top) section along the long axis, down stream valleys from the summit of La Soufrière to the sea and, (bottom) section perpendicular to the first sketch, across the axis of the stream valley. These drawings are based upon series of Photographs taken from Vieux Habitants at 7 minutes, 30 seconds after the eruption began.

(b) Map of the approximate area covered by the dense clouds of steam and tephra erupted on October 2. The area covered by the clouds (stippled) moved down the valley of the R. Noire and R. des Pères in 6 minutes (1638 h to 1644 h local time) and then began to spread laterally and forward across the sea. By 1740 (1 hr, 2 min after the beginning of the eruption) the lateral growth of the cloud had blocked the view of the setting sun from Marigot.

FIG. 7 – Photograph of the eruption of October 4, from Basse-Terre (9 km southwest of the dome). The tephra-laden cloud drops to a level 100 to 200 m below the summit, flowing down the valley of the R. Noire. At a distance of 4 km from the summit, it rises again as a more diffuse cloud, to an altitude of about 2.5 km.

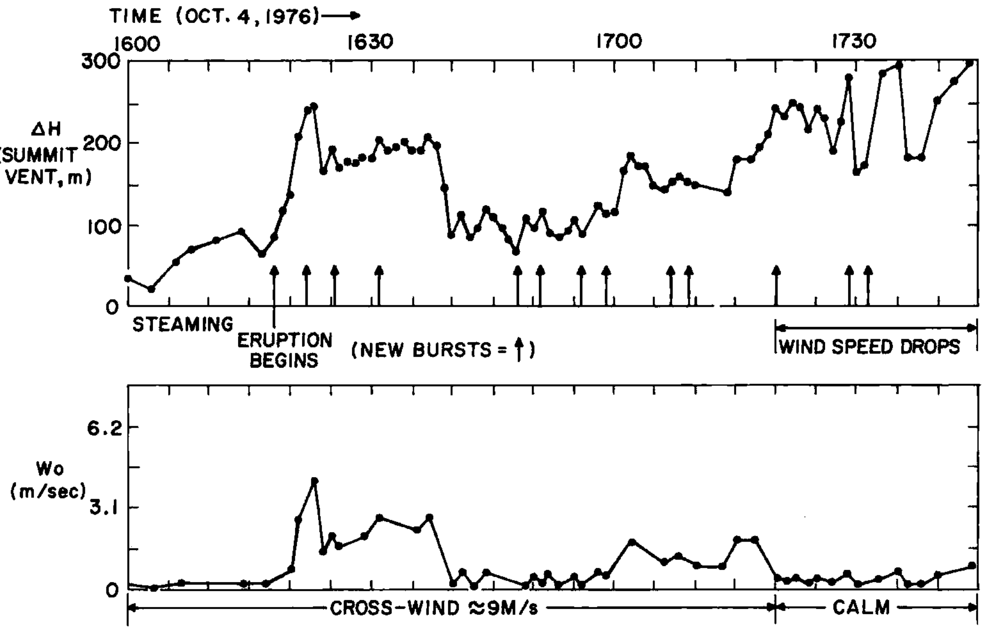


FIG. 8 – Eruption sequence, evening of October 4, from 1600 to 1750. ΔH and W_0 are plotted versus time. The horizontal wind velocity dropped at about 1720, allowing steam clouds to rise to 300 m above the summit.

ced clouds rising to nearly 300 m during windless conditions. Individual phreatic explosions during this period were marked by a darkening of the cloud to a medium or dark gray. Individual bursts were separated by 2 to 5 minute periods, with some explosions (bursts) lasting up to 11 minutes. Near the end of this activity, the steam clouds turned white and contained very little tephra.

Other Activity:

Other phreatic explosions are less well documented. The explosion of 22 Sept. may have reached an elevation of 3.5 km above the vent, but this was above the field of view of the Automax camera. However, according to the camera data obtained, this eruption, which consisted of 2 major explosions, 5 minutes apart, lasted for about 27 minutes.

Although not observed by the authors, a group of observers were caught at the summit during the phreatic explosions of August 30, 1040 AST. The tephra and block-fall was heavy in the summit region. It was not possible, due to clouds, to observe the eruption cloud from Basse-Terre. The blast heard in Basse-Terre was similar in magnitude to a sonic boom, followed by a low roar for about 3 minutes. Observers at the summit did not comment on any sound other than a low hissing noise. The tephra falling on them was cool to touch, very sticky and fine-grained and several small lahars were observed by those at the summit.

Deposition of Fine-grained Tephra by Phreatic Explosions

Using data from the sequence camera and individual observations of the eruption at 1638 hrs, Oct. 2, it is possible approximately to define the mechanism of the event. This event was selected because it seems to be fairly typical and is the best-documented. Although both vents (summit and southeast fissure) were active, only the summit vent was laden with tephra. The southeast vent erupted steam only.

Based on maps provided by the observatory and helicopter photographs of the summit, the area of the main vent (G. Tarissan) is about 600 m^2. Velocities based on the plume rise formula (Appendix) are listed in Table 2.

TABLE 2

Velocity (m/sec)	*Period of Activity (min)*
60	9
40	4
20	6

If we assume that steam and tephra were being released from a vent with an area of 600 m^2, at velocities listed in Table 2, then a volume of 29.5×10^6 m^3 was erupted from 1638 hrs to 1657 hrs (19 minutes), the period of explosive activity. The corridor along which the eruption cloud flowed and along which tephra was deposited covers an area of 35 km^2, exclusive of any tephra-fall over the sea. Based on only a few thickness measurements (4 mm to 1 cm closest to the dome to 0.1 mm at a distance of about 8 Km) the total volume of tephra deposits from this phreatic eruption is about 53×10^3 m^3. The eruption cloud must have entrained at least 2.6 kg/m^3 (assuming a bulk ρ of 1.5 gm/cm^3 for the tephra) of erupted steam. This is clearly feasible for a fluidized system of clay - silt - fine sand size tephra. According to SPARKS (1976), entrainment of material of that particle size in a fluidized system (steam passing through altered, fine-grained rock and clay) would require velocities as low as 10 cm/sec (0.1 m/sec). The observed velocities (20 to 60 m/sec.) are more than adequate to entrain large volumes of fine-grained tephra within the vent and carry it up in the eruption cloud.

As was described earlier, the tephra-laden steam cloud flowed down valleys as a density current. The observed average velocity of 26 m/sec for the Oct. 2nd cloud exceeds considerably the average wind velocity of 10 m/sec. It therefore must have flowed as a gravity-driven density current.

TEPHRA FROM THE PHREATIC ERUPTIONS

Twenty tephra samples, from 12 phreatic eruptions (12 August to 1 November, 1976) were studied. A manuscript is being prepared on that subject by the Laboratoire de Géochimie et Cosmochimie, Institute de Physique du Globe and Los Alamos Scientific Laboratory; some of its main conclusions are summarized here.

Tephra from the phreatic eruptions is fine-grained with a mean grain size of 4.7 ∅ (38 μm) sorting = 2.03 ∅, very poorly sorted) (1), forming very thin, gray sticky deposits containing accretionary lapilli.

Most of the > 38 μm fraction consists of hydrothermally altered andesite or dacite fragments. The degree of alteration ranges from a trace of hematite on grain surfaces to clay-pyrite mixtures, exhibiting only relict textures to identify them as fragments of lava. Plagioclase grains, ranging in composition from An_{50} to An_{88}, are present in the tephra as broken subhedral crystals exhibiting progressive and oscillatory zoning. Pyroxenes are mostly pale yellow to pale pink orthopyroxene (Wo_3 En_{63} Fs_{34} to Wo_4 En_{52} Fs_{44}). Smaller amounts of clinopyroxene (Wo_{41} En_{41} Fs_{18} to Wo_{43} En_{37} Fs_{20}) are also present. Amorphous masses of hematite and well-developed pyrite grains are found in all of the samples. Glass particles (rhyolitic to andesitic) are present in small amounts. In all cases, the glass exhibits some degree of alteration and apparently was derived from the glassy groundmass of the dome lavas. There was no evidence in the tephra of fresh (juvenile) magma.

The La Soufrière dome is composed of silicic andesite, with phenocrysts of plagioclase, augite and pigeonite making up about 50% of the rock. Tephra from the phreatic eruptions were derived from hydrothermally-altered and acid-leached rocks of the dome. The lithic, glass and crystal components of this tephra are identical in composition and texture to the dome lavas.

(1) Sample from the phreatic eruption of October 2, collected at Matouba, 3 km SW of the summit. The statistical parameters of grain size are those of FOLK (1968).

DISCUSSION

The absence of unaltered juvenile glass in the tephra deposits from the 1976 activity of La Soufrière is highly significant. This indicates that new magma was not the *direct* driving mechanism for the eruptive activity. Rather the activity was most probably the result of increased thermal pulses affecting groundwater circulation in a vapor-dominated system. The thermal pulses may have been initiated by a major change or disruption of the existing hydrothermal system by the introduction, at *depth*, of a magma body. Presence of a magma body is suggested by the greatly increased shallow seismic activity (*Bulletins of l'Institut Physique du Globe*).

Most vapor-dominated geothermal systems are located in elevated areas of groundwater recharge where groundwater movement is downward and outward (HEALY, 1976). The La Soufrière dome is the highest point on the island, and is the focus of the island's heaviest rainfall (LASSERRE, 1961). Within such systems, boiling or warm springs may be located at the base of the elevated region and the steam will pass upward where it may be explosively released (HEALY, 1976). Again, this is the case at La Soufrière (summit at 1466 m), where there are numerous hot springs around the base, at elevations of 950 to 1200 m (from 1 : 20,000 scale topographic maps of Guadeloupe).

What, then, controls the sporadic phreatic eruptions? The more explosive activity may be related to the rate of recharge of meteoric water within the dome, the decrease in pore pressure during fortnightly tidal minimums, or both. RINEHART (1976) found that slight changes in state of strain modify pore pressure within permeable rock units and thus control the flow rates. Tidal changes do alter the flow characteristics of some geothermal systems, especially geysers. Fortnightly components of 11 to 16 days (RINEHART, 1976; MAUK and JOHNSON, 1973) have been observed to affect geysers and erupting volcanoes, and may be a controlling factors for some of the explosive activity at La Soufrière. As was noted earlier, one of the periods of accelerated phreatic activity followed extremely heavy rains by 2-1/2 hours.

Whatever the cause of the phreatic explosions, we suggest that vapor-dominated fluids eroded vent fillings and walls, and erupted fine-grained tephra and steam. Observed velocities of erupted steam are more than adequate to entrain fine-grained clastic material within the vents. The simultaneous eruption of tephra-laden and tephra-poor steam clouds from the same vent has several implications. It may be that there were differences in the gas velocities along the length of the vent, and thus differences in the ability to erode vent walls, or there may be lateral changes in the degree of vent-wall alteration and the ease with which the alteration products were eroded and carried out.

After rising buoyantly, the «cool» tephra-laden clouds were pushed downwind and moved as density currents along stream valleys radiating from La Soufrière. Movement of the clouds as density currents is supported by the fact that observed clouds were moving faster than the predominant winds and they were «channeled» by topography. For example, the vapor-tephra cloud from the eruption of October 2 was confined to a valley until it reached the sea and began to spread laterally.

Thin, corridor-like tephra deposits of fine-grained, hydrothermally altered dome rock, radiating from dome summits, and associated with laharic breccias may be used to identify past periods of intense hydrothermal activity at a volcano. Such deposits may be useful in studying past trends or eruptive cycles. Deposits similar to those deposited by the phreatic activity at La Soufrière have been described at Mt. Pelée, Martinique, interbedded with silicic pumice deposits (ROOBOL and SMITH, 1976).

APPENDIX

Methods

To asses the mechanics of the eruption clouds, a 35-mm automatic camera (Automax) with a 50-mm lens was emplaced on the Plateau du Palmiste. The camera was located 4 km from the summit of La Soufrière and oriented normal to most of the eruption clouds. One color photograph was taken every minute. Although there were some problems with persistent cloud cover and batteries, a number of small eruptions and several days of normal fumarolic activity were photographed. Measurements of clouds are outlined in Fig. 9.

Other photographs were taken of the activity from BassTerre, Matouba, St. Claude, the summit car park, Vieux Habitants, and Marigot with hand-held 35-mm cameras having 50- to 300-mm lenses.

Weather data necessary to analyze the eruption cloud photographs were obtained from the National Climatological Center, Ashville, N.C., U.S.A. The nearest stations where were data available for this time period were Antigua, B.W.I. (Sonde data) and Basse-Terre, St. Kitts, B.W.I. (groundbased data). It was used, along with subjective descriptions of the weather by observers at the volcano.

To estimate the vertical exit velocities of steam from vents on Soufrière, we used methods developed by BRIGGS (1969) and

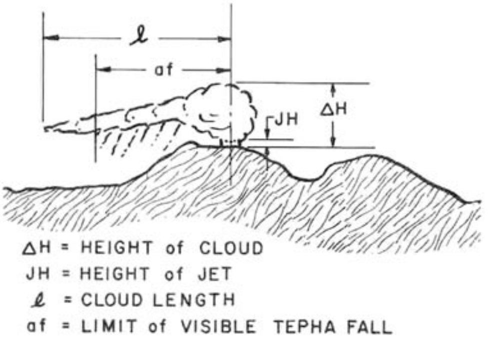


FIG. 9 - Schematic drawing, showing the measurements made of each photograph from the Automax (sequence) camera.

summarized by Settle (1976) for assessing the rise of industrial plumes. From the cameras, the height of the cloud is determined, the average cross - wind speed is estimated from Sonde data, and the vent width estimated from maps and photographs.

The formula from BRIGGS (1969), for stable conditions, windy, is:

$$\Delta H = 4.0 \left(\frac{F}{\mu s} \right)^{1/3}, \qquad (1)$$

where

ΔH = Plume rise height aove vent (m).

D = Vent diameter [in this case, the vent *width* was 10 m; the vents were fissures, not circular craters].

W_0 = Vertical exit velocity at the vent mouth (m/s).

ΔT = Difference in absolute temperature between ambient air and effluent gas (79°K).

T_s = Absolute temperature of effluent stack gas (assume 373°K).

T_a = Absolute of ambient atmosphere (292°K).

F = Buoyancy flux = $g\left(\frac{\Delta T}{T_s}\right) W_0 \left(\frac{D}{2}\right)^2$, ($m^4/sec^3$)

S = Atmospheric stability parameter = $\frac{g}{T_a} \frac{\sigma\Theta}{\sigma z}$,

$$\frac{\sigma\Theta}{\sigma z} = \Gamma + \frac{9.8\ {}^{\circ}K}{1000\ m}$$

Γ = Environmental lapse rate $\frac{\sigma T}{\sigma z} \left(\frac{{}^{\circ}K}{km} \right) = -7$

μ = Average cross-wind speed (9 m/s)

g = Gravitational acceleration.

$\sigma\Theta$ = Potential temperature.

σz = Elevation

The vertical exit velocities were approximated in the following way:

$$F = \left(\frac{\Delta H}{4} \right)^3 \mu s \qquad (2)$$

$$W_0 = \frac{F}{g\left(\frac{\Delta T}{T_s}\right) \left(\frac{D}{2}\right)^2} \qquad (3)$$

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